

****Volume Title****

*ASP Conference Series, Vol. **Volume Number***

****Author****

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Astrometric determination of WD radial velocities with Gaia?

Stefan Jordan¹, Jos de Bruijne²

¹*Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität
Heidelberg, Mönchhofstr. 12–14, D-69120 Heidelberg, Germany*

²*European Space Research and Technology Centre (ESA/ESTEC) in
Noordwijk, the Netherlands*

1. Introduction

Usually, the determination of radial velocities of stars relies on the shift of spectral lines by the Doppler effect. Russell & Atkinson (1931) and Oort (1932) already noted that due to the large proper motion and parallax of the white dwarf (WD) van Maanen 2, a determination of the perspective acceleration of the proper motion would provide a direct astrometric determination of the radial velocity which is independent of the gravitational redshift. If spectroscopic redshift measurements of H_α and H_β NLTE cores exist, a purely astrometric determination would allow disentangling the gravitational redshift from the Doppler shift.

The best instrument for measuring the tiny perspective acceleration is the Gaia satellite of the European Space Agency, aiming at absolute astrometric measurements of one billion stars down to 20th magnitude with unprecedented accuracy. At 15th magnitude, the predicted angular accuracy of Gaia is ~ 20 micro-arcseconds (μas). In this article, we estimate whether it is possible to measure the radial velocity of WDs astrometrically by the exchange of proper motion into radial velocity during the 5-year mission of the satellite or by combining Hipparcos data with the position measurements at the beginning of the Gaia mission (the Hundred-Thousand-Proper-Motion project HTPM).

2. Perspective acceleration

Since stars move with (almost) constant velocity through space, the proper motion $\mu = (\mu_{\alpha*}^2 + \mu_\delta^2)^{1/2}$ as seen from an observer varies inversely with the distance to the object and also changes due to the varying angle between the line of sight and the space-velocity vector (see, e.g., Dravins et al. 1999, see also Fig. 1). Both effects lead to an apparent change in proper motion of $\dot{\mu} = \frac{-2\mu\pi v_r}{1 \text{ AU}}$ (van de Kamp 1967; Murray 1983), where π denotes the parallax of the star. Conversely, this means that the radial velocity can be determined astrometrically from $v_r = -\frac{\dot{\mu} 1 \text{ AU}}{2\pi\mu}$.

As summarized by Dravins et al. (1999), past attempts to measure perspective acceleration yielded barely significant or spurious results. A high accuracy in terms of the

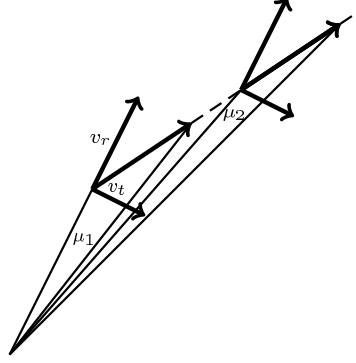


Figure 1. Perspective acceleration: let μ_1 be the proper motion at the beginning of the Gaia mission and μ_2 the proper motion at the end of the mission. As a (nearby) star passes the observer (Sun), proper motion is continuously exchanged into radial velocity. Measuring the decrease of the proper motion allows astrometric determination of the radial velocity, without the use of spectroscopy.

astrometric radial velocity was only obtained for Barnard's star (van de Kamp 1981) and for van Maanen 2 (Gatewood & Russell 1974). By combining positions and proper motions from Hipparcos and old position measurements from the Astrographic Catalogue (for a description, see Eichhorn 1974), Dravins et al. (1999) determined astrometric radial velocities for sixteen stars, albeit with modest precisions.

3. The Hundred-Thousand-Proper-Motion project

The HTPM project is part of the first intermediate release of the Gaia data and will contain the proper motions of $\sim 113,500$ stars using an ~ 23 -year baseline. The proper motions will be based on the Hipparcos data (positions, proper motions, and parallaxes) at the first epoch (1991.25) and Gaia positional data at the second epoch (~ 2014.25). For this catalogue, de Bruijne & Eilers (2012) determined that for nearly 100 stars, the radial velocities available in the literature are insufficiently precise to correct for the perspective acceleration. Generally, stars with a large product $\mu\pi v_r$, i.e., nearby, fast-moving stars, are good candidates for measuring radial velocities through astrometry.

4. Perspectives for white dwarfs

We estimated the accuracy of astrometric v_r determinations with Gaia by investigating the 39 WDs either having Hipparcos astrometry themselves (Vauclair et al. 1997) or wide companions with Hipparcos measurements (Gould & Chanamé 2004).

First, we estimate the accuracy using HTPM data only. In this case, we have positions $\phi_{1991.25}$ and proper motions $\mu_{1991.25}$ determined at epoch 1991.25 and only positions $\phi_{2014.25}$ from Gaia at ~ 2014.25 . $\phi_{2014.25}$ combined with the $\phi_{1991.25}$ positions provide a second proper-motion measurement (symbolically: $\mu = (\phi_{2014.25} - \phi_{1991.25})/T$). The standard error of the astrometric v_r can be estimated by (Dravins et al. 1999)

$$\epsilon(v_r) \approx \frac{2 \cdot 1 \text{ AU}}{T\pi\mu_{1991.25}} \left[\frac{\epsilon(\phi_{1991.25})^2 + \epsilon(\phi_{2014.25})^2}{T} + \epsilon(\mu_{1991.25})^2 \right]^{1/2}, \quad (1)$$

with $T = 2014.25 - 1991.25$ and $\epsilon(\mu)$ the accuracy of the proper-motion measurements. The expected HTPM proper-motion standard errors are $\sim 30\text{--}190 \mu\text{as yr}^{-1}$, depending on magnitude. For our 39-star sample, the best accuracy for the astrometric radial velocity using only HTPM data is 282 km s^{-1} for HIP57367 (column 10 in Table 1), which is too large to be of any scientific value.

Second, we estimate the accuracy using the Gaia data only. The achievable accuracy for quasi-continuous observations during a period of length L (5 years in the case of Gaia) is given by (Dravins et al. 1999):

$$\epsilon(v_r) \approx \sqrt{15} \cdot \frac{\epsilon(\mu) \text{ 1AU}}{L\pi\mu}. \quad (2)$$

Since all stars in our sample are bright for Gaia, the end-of-mission accuracy $\epsilon(\mu)$ amounts to $\sim 3.5 \mu\text{as yr}^{-1}$ (de Bruijne 2012). For this case, three stars (HIP 3829 = van Maanen 2, 21088 = Gl 169.1B, and 57367 = GJ 440) have predicted standard errors below 10 km s^{-1} (column 12 in Table 1). Five objects have predicted standard errors between 20 and 60 km s^{-1} , which is of the order of the mean gravitational redshift in DA WDs, which is about 33 km s^{-1} (Falcon et al. 2010).

5. Conclusions

An astrometric determination of radial velocities of WDs with Gaia data is possible but limited to a few bright, nearby objects. The accuracy of the HTPM catalogue, which will be released early during the Gaia mission, is by far not large enough for an astrometric radial velocity determination of WDs. A breakthrough in this area would require a second micro-arcsecond astrometry mission, the data of which would have to be combined with the Gaia data (see, e.g., Anglada-Escudé & Debes 2010).

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Table 1. Predicted standard errors of astrometric radial velocities based on HTPM data and on Gaia data for 39 WDs (all Hipparcos entries of white dwarfs themselves plus all Hipparcos stars with known white-dwarf companions; HIP35307 has been omitted since it has a negative parallax measurement). Columns: 1: Hipparcos identifier; 2: *H_p* magnitude; 3: parallax in mas from the XHIP Catalogue (Anderson & Francis 2012); 4: parallax error in mas (XHIP); 5: proper motion in $\mu\text{as yr}^{-1}$ (XHIP); 6: literature radial velocity in km s^{-1} (XHIP); 7: literature radial-velocity error in km s^{-1} (XHIP); footnote: quality flag (A = good, ..., D = bad; XHIP); 8: perspective acceleration in $\mu\text{as yr}^{-2}$; 9: accumulated effect of perspective acceleration on position over 23 yr in μas (the HTPM temporal baseline); 10: HTPM astrometric radial velocity standard error in km s^{-1} ; 11: accumulated effect of perspective acceleration on position over 2.5 yr in μas (half the Gaia mission timeline); 12: Gaia astrometric radial velocity standard error in km s^{-1} .

1	2	3	4	5	6	7	8	9	10	11	12
002600	10.42	11.22	1.52	227.21	49.98	0.17 ^A	-0.26	-68.93	$3 \cdot 10^5$	-0.81	1040
003829	12.56	234.60	5.90	2978.19	263.00	4.90 ^D	-375.85	-10 ⁵	444	-1175	3.8
008709	12.55	64.53	3.40	122.18	64.00		-1.03	-273	23738	-3.23	336
011650	12.85	37.52	5.17	75.98	-5.70	2.90 ^D	0.03	8.79	191848	0.10	930
012031	12.37	10.90	3.94	83.22	55.20	7.40 ^D	-0.10	-27.09	149151	-0.32	2922
014754	11.44	98.50	1.85	109.00	33.80	3.20 ^D	-0.74	-196.33	12007	-2.32	247
018824	6.86	19.35	0.63	373.70	10.21	0.20 ^A	-0.15	-39.94	24697	-0.47	367
021088	10.79	179.27	3.23	2426.09	27.90	0.40 ^A	-24.82	-6564.89	570	-77.56	6.1
021482	8.23	56.02	1.43	276.52	36.02	0.08 ^A	-1.14	-301.87	4415	-3.57	171
023692	11.72	16.70	2.97	91.90	69.00		-0.22	-57.29	94943	-0.68	1727
027878	7.88	18.68	0.81	260.59	16.10	15.60 ^B	-0.16	-42.40	19235	-0.50	545
029788	6.56	26.72	0.29	319.81	-1.50	0.67 ^A	0.03	6.93	3575	0.08	310
032560	12.09	63.53	3.55	967.42	80.00	5.00 ^D	-10.06	-2660.08	2860	-31.43	43
037853	5.48	65.75	0.51	1709.12	106.16	0.10 ^A	-24.40	-6454.15	833	-76.25	24
054530	8.82	24.90	0.98	234.45			0.03	6.98	24466	0.08	454
056662	12.53	63.26	3.60	147.94	17.00	42.00 ^D	-0.33	-86.07	18193	-1.02	283
057367	11.59	217.01	2.40	2687.68			2.64	697.36	282	8.24	4.5
059519	10.10	22.18	1.49	428.69			0.04	11.37	15708	0.13	279
064766	12.67	25.96	6.38	192.62	44.40	14.40 ^A	-0.45	-120.11	96111	-1.42	530
065877	12.39	55.50	3.85	1205.95	35.60	4.70 ^A	-4.87	-1289.08	2678	-15.23	40
066578	12.84	38.29	3.02	404.25	1.00		-0.03	-8.37	17732	-0.10	171
073224	9.98	16.51	1.66	208.09			0.02	4.11	37400	0.05	772
077358	6.15	65.13	0.40	467.30	-6.70	0.74 ^A	0.42	110.32	1008	1.30	87
080300	10.99	76.00	2.56	76.45	13.00	0.10 ^D	-0.15	-40.87	22075	-0.48	456
080522	10.20	17.86	2.12	492.02	90.70	2.70 ^A	-1.63	-431.20	15537	-5.09	302
082257	12.38	94.04	2.67	326.13	41.60		-2.61	-690.24	6596	-8.16	86
092306	9.80	12.68	0.76	182.50			0.01	2.77	27645	0.03	1146
095071	12.37	91.31	4.02	173.58			0.07	18.95	10385	0.22	167
101516	11.55	64.32	2.58	693.46	71.00	7.40 ^D	-6.48	-1713.31	2495	-20.24	60
102207	12.42	48.22	3.77	367.77	1.80		-0.07	-17.27	12129	-0.20	149
102488	2.64	44.86	0.12	484.93	-11.60	0.30 ^A	0.52	136.52	1754	1.61	122
103393	11.91	56.54	3.92	818.64	-42.70	1.00 ^A	4.04	1069.26	8565	12.63	57
106335	9.86	20.26	2.01	413.78	-109.60	0.40 ^A	1.88	497.09	11240	5.87	316
107968	12.88	37.51	4.41	302.18	32.00		-0.74	-196.23	13009	-2.32	234
110218	10.30	20.30	1.40	420.92			0.04	10.22	13211	0.12	310
113231	8.14	27.22	1.12	552.73	-27.68	0.14 ^A	0.85	225.31	6233	2.66	176
113244	11.30	40.89	2.12	447.31	-1.00	10.00 ^D	0.04	9.90	7496	0.12	145
113786	8.78	14.97	0.79	160.19	13.63		-0.07	-17.68	35508	-0.21	1105
117308	11.40	19.11	3.04	300.40			0.03	6.86	32444	0.08	462